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To Mr. F.J. Kee
Director of Research

FIBER OPTICS POTENTIAL FOR FISH DIVERSION

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Present underwater strobe lights to divert fish away from water intakes at generating stations are difficult to modify and maintain. In this report an analysis is done on an alternative system with land-based light sources and optical fibers to conduct the light underwater. With a laser as the light source, such a system is found to be technically feasible. Cost estimates are given for a suitable laser and optical fiber.

INTRODUCTION

Laboratory experiments and field trials at Pickering have been done on fish behaviour in the presence of underwater strobe lights for the purpose of diverting fish away from cooling water intakes. Both maintenance and experimental modifications are hampered and rendered costly by the underwater placement of these light sources. Therefore, this study has been done for the Environmental Studies and Assessments Department as part of the Capitalized Once Through Cooling (COTC) program, to assess the potential use of optical fibers to conduct light from dry-land sources to underwater projection points.

The conceptual system consists of three parts: a light source or sources, a number of underwater light pods where the light would be released, and interconnecting optical fibers suitably protected for underwater use.

In the simplest system concept, each underwater light pod would be connected to its own individual light source by a single optical fiber. For this to be technically feasible, it is necessary to identify an optical fiber capable of transmitting the light pulses, and a powerful light source which is capable of being coupled efficiently into an optical fiber.

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Other system configurations are possible. For example, the light from a single, powerful laser could be split into a number of beams which could then be coupled into individual fibers, one for each of several underwater pods. Alternatively, if the best source were a diffuse one, a number of optical fibers could be positioned around it, in order to collect a larger portion of the light.

The best system configuration, then, would be chosen by matching the components to each other in a cost-effective way.

ILLUMINATION REQUIREMENTS

The present underwater strobe lamps used for fish diversion produce about 1 joule of optical energy per pulse, at a pulse rate of 3 per second. The pulse length is less than 1 millisecond, and the spectrum is approximately white light. We shall take these performance figures for the existing strobe lamps as the specifications for a fiber-optic system.

It should be noted that these requirements call for the transmission of optical power levels several orders of magnitude greater than those used in fiber optic communications.

OPTICAL FIBERS

The special requirements of the fish diversion application preclude the use of the majority of optical fiber products, which have been developed for communications. Low cost plastic fibers are used for short distance data links between computers on the same site, for example. In long distance applications, glass fibers specially prepared from ultra-pure materials have been used in communication links with repeater stations required only every 30 km. It has been found that the best wavelengths to use for communications are in the infrared region of the spectrum, where the fibers exhibit the least absorption of light. Originally the fibers used for long distance communications were as thick as a hair, but the trend now is toward monomode fibers with a core diameter of about 10 micrometers. Usually only a single fiber is used for a given channel, although occassionally a bundle of fibers is used to ensure redundancy in case a single fiber breaks.

The use of optical fibers for illumination pre-dates their application in communications. A generation ago, Du Pont began supplying the auto industry with plastic fibers for tail light monitors. These products are still available as a 1 mm diameter single fiber or a more flexible bundle of a dozen thinner fibers. They are useful for remote illumination over distances of one or two meters. Beyond this distance the light intensity is noticeably reduced. Another product, from American Optical, is a larger diameter bundle of fine glass fibers. These units are very flexible because of the thin fibers, and can collect a

relatively large fraction of the light from a light bulb because of their large overall diameter. Such fiber optic bundles unfortunately carry a substantial cost penalty.

There is, however, one product on the market which appears to be technically suitable for the fish diversion application. Quartz Products Corporation markets special silica optical fibers with low attenuation and high power handling ability, in sizes up to 1 mm diameter/1/. The largest of these fibers would be marginally suitable for fish diversion.

A 1 mm diameter fiber would have no problem transmitting the average power level of 3 watts needed for fish diversion. Robertson, at Sandia Laboratories, has successfully transmitted this power level/2/. The problem in fish diversion is the fact that the light must be pulsed.

The main consideration with pulsed light is whether or not the surface of the input end of the fiber can withstand the pulse. Damage is known to occur when the energy density rises over 130 to 150 joules per square centimeter/3/. Thus, for the 1 joule pulses needed for fish diversion, the fiber must have a diameter of 1 mm or more to avoid surface damage to the input end.

The 1 mm quartz fibers, discussed here for fish diversion, have their best transparency in the infrared, a property held in common with essentially all other types of optical fibers. At the visible wavelengths used for fish diversion, the transparency is less, and half the light would be absorbed in a distance of about 100 metres.

Since the 1 mm size is the largest quartz fiber currently available, and since the maximum input energy it can tolerate is 1 joule, the maximum pulse energy which could be delivered to the output end would be half a joule for a run of 100 metres, or a quarter of a joule for 200 metres, and so forth.

At the time of writing, the price of 1 mm diameter quartz optical fiber was about $20 per metre. The next size smaller, which could be used if somewhat lower power were deemed sufficient, costs about $6 per metre.

With these costs for optical fibers, it would appear that the use of multiple fibers to feed one underwater light pod would be ruled out. In fact, these fiber costs may dictate that the optical fiber runs be kept under a few tens of metres.

COUPLING A LIGHT SOURCE TO AN OPTICAL FIBER

For a light beam to be successfully launched into an optical fiber, two conditions must be met. The first condition concerns the diameter of the beam and the second concerns its angular divergence. These quantities, and their implications, are analyzed in the Appendix.

Briefly put, the diameter of the light beam must match that of the fiber's core. If the beam has a greater diameter, light will be lost. If it has a lesser diameter, a small pit will be melted in the input face of the fiber by the high energy pulses used for fish diversion.

The second condition is that the angular divergence of the input light beam may not exceed the limit set by the fiber's acceptance angle. This condition arises from the mechanism by which optical fibers conduct light - total internal reflection. If the input rays exceed the angle for total internal reflection, they escape out through the side of the fiber. On the other hand, there is no penalty incurred if the source's angular divergence is less than the fiber's acceptance angle.

The two quantities discussed above are not independent quantities, rather, they are related by the "brightness theorem" discussed in the Appendix. A lens may be used to focus a light beam down to a smaller diameter, with an attendant increase in angular divergence. On the other hand, a collimator may be used to provide a beam of "parallel" light with small angular divergence. However, such a collimated beam will always have a larger diameter than the original. The algebraic relationship governing trade-offs between beam diameter and angular divergence is that their product is inversely proportional to the brightness of the source.

In this context, brightness is to be distinguished from intensity, which is the total power emitted. A source's brightness is its power output per unit of surface area into a cone of unit solid angle. If a distant laser, even a low power one, is viewed beside a high power incandescent light bulb, the laser will appear as a bright point of light, considerably brighter than the incandescent source of greater intensity.

Since a laser is a light source of high brightness, it can deliver a narrow beam with small angular divergence. This is idea for coupling into an optical fiber. On the other hand, a diffuse source such as an incandescent light bulb or a flash tube has low brightness in comparison to a laser. As a consequence, there is no efficient means of coupling such sources into an optical fiber. Even with a reflector and a condensing lens, as found in slide projectors for example, very little of the light could be launched down the fiber. The attempt to collect a greater portion of the light by installing a larger

lens would yield a beam which, when focussed down onto the end of the fiber, would have excessive angular divergence. Increasing the power of a diffuse source is generally of no value, since the higher power is achieved by making the source bigger, not brighter. To make an incandescent source brighter, it must be operated hotter. This reduces its life. Similarly, a flashtube would have to be operated at a higher current density, and this would shorten the life of the electrodes.

A formula, Equation 12, is given in the Appendix for the maximum possible efficiency of coupling a diffuse source to a fiber. This efficiency is increased by the square of the fiber's diameter and numerical aperture, and is decreased inversely as the square of the source size. Thus it is advantageous when using non-laser sources, to have a large diameter single fiber, or a fiber optic bundle of large diameter. The numerical aperture, given by the sine of half the acceptance angle, should be as large as possible. And a "point-of-light" source is advantageous over a larger size source.

The next sections contain more detailed discussions of three types of pulsed light sources: lasers, arc lamps, and strobe lights and flashtubes.

LASERS

For fish diversion, the light source is required to produce pulses of higher energy than those provided by most laboratory lasers. In this application, three pulses, each of one joule energy, are required each second. The average power, then, is three watts.

The argon ion laser produces over one watt of green light; but unfortunately it is not a pulsed laser. Neodymium:YAG lasers are pulsed lasers capable of yielding over one joule pulses in the near infrared. With a frequency doubling crystal, green light is produced, though it is difficult to achieve one joule pulses after doubling. Ruby lasers can produce pulses of red light over one joule, but can not be fired three times per second. The familiar helium-neon laser is a continuous laser rather than a pulsed laser and is capable only of low power output.

The most promising type of laser for fish diversion would be the more recently developed dye laser with coaxial flashlamp. Although the spectral purity and stability are less than those of other lasers, these are properties not needed for fish diversion. Similarly, pulses of ultrashort duration are not needed.

The Phase-R Corporation/4/ sells a suitable dye laser for approximately $10,000 at the time of writing. Model DL-2100C produces pulses up to 1.5 joules in energy. The maximum

repetition rate is 5 pulses per second. Both of these quantities, energy per pulse, and pulse repetition rate, allow a slight margin over the illumination requirements for fish diversion. The pulse length of 250 nanoseconds is several orders of magnitude shorter than actually required. The wavelength of light produced can be tuned from 220 to 960 nanometers, that is, across the entire visible spectrum, and somewhat beyond.

Thus, this particular laser appears to be a sufficiently powerful laser to replace one of the underwater strobe lamps presently in use. Its output is tunable to any desired colour. Being a laser, it can be efficiently coupled to an optical fiber.

Maintenance would primarily entail replacement of the coaxial flashlamp every one to two months. Consequently, annual operating costs would be roughly as great as the initial capital cost.

Higher power lasers, which could service more than one underwater light pod, are available. However, at the present time, their proportional increase in cost appears to be greater than the increase in power. In future, lasers with more power per dollar may become available as the technology advances and as the sales volume grows.

ARC LAMPS

A specialized product is available from Photochemical Research Associates/5/ with properties lying between those of lasers and flashtubes. This is a pulsed arc lamp which has sufficiently powerful pulses for fish diversion.

Usually, arc lamps are operated in continuous mode as a light source with greater brightness and higher intensity than incandescent or gas discharge sources. The larger arc lamps are used as solar simulators, for example. Arc lamps are also available with closely spaced electrodes of small dimensions. One model, filled to high pressure with xenon gas, has an arc size only 0.3 mm long by 0.3 mm wide.

A calculation based on the Appendix shows that up to 7 watts of optical power could be successfully coupled into a typical 1 mm fiber by one of these short-arc lamps with an electrical input of 500 watts.

To operate an arc lamp in pulsed mode, a "simmer" current is allowed to flow through it continuously. Then when a burst of light is required, a capacitor bank is discharged through the lamp. With this technique, pulses of light suitable for fish diversion via optical fibers could be obtained.

The critical area for this type of light source is its lifetime. The supplier, Photochemical Research Associates, quotes a life for the arc lamp as "several thousand shots". At three pulses per second for fish diversion, the lamp would last only an hour at best.

It would appear that the high brightness of the short-arc lamp is attained by sacrificing the electrodes.

STROBE LIGHTS AND FLASHTUBES

The present light sources placed in underwater pods for fish diversion are strobe lights. They are constructed from a length of quartz tubing formed into a coil and filled with xenon gas at low pressure, leading to a much greater lifetime than that of the arc lamps discussed above. Such strobe lights, however, are much too diffuse for efficient coupling to an optical fiber.

Another product in the same general class, with better prospects for coupling to optical fibers, is a bulb-type flashtube available from EG&G/6/. Their model FX-132 has a life of 2 million flashes at an input energy of 80 joules per pulse. At this energy, the arc diameter is 16 mm, yielding, unfortunately, a coupling efficiency of only 1.6×10^{-5} for coupling into a typical 1 mm optical fiber with numerical aperture of 0.22. Assuming an electrical efficiency of 30%, the optical energy coupled into the fiber would be about a factor of 1000 less than that needed for fish diversion.

Thus, flashtubes of all types appear to be ruled out for fiber optic fish diversion.

FISH RESPONSE TO A "POINT-OF-LIGHT"

A 1 joule pulse emitted from the output end of an optical fiber would be about 1000 times brighter than a 1 joule pulse emitted by a strobe light. It would look like an exceedingly bright point of light.

If fish response to pulses of light from a "point" were tested, it could turn out that enhanced avoidance would be observed.

In this case, a fish diversion system could be designed with fewer underwater pods. Alternatively, each pod could be supplied with optical pulses of lower energy. Then one laser could handle several underwater pods.

CONCLUSIONS

A fiber optic illumination system for fish diversion could be assembled with off-the-shelf components. Pulsed dye lasers with adjustable colour are available for approximately $10,000. One of these lasers would be equivalent in power output to one of the strobe lights in the present system. Annual operating costs (mainly to replace the flashlamp) would be roughly equal to the initial capital cost of the laser. Quartz optical fiber large enough to handle the high energy pulses, and transparent enough for runs up to a few hundred meters, is available for about $20 per meter.

Conventional light sources can not be used. The amount of light from a flashtube which can be successfully coupled into an optical fiber would be about a factor of one thousand too small. More of the light could be collected by using a large number of optical fibers, but then their cost would become excessive. Light from a high pressure arc lamp with a short arc could be coupled into a fiber with considerably higher efficiency, but in pulsed operation the lamp would last only an hour.

In future work, the response of fish to the high brightness "point-of-light" emitted from the output end of an optical fiber could be assessed. If enhanced avoidance were discovered, then less power would be required from each underwater pod, and a single dye laser could handle several pods.

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APPENDIX

FORMULAS FOR COUPLING LASERS AND LAMPS TO OPTICAL FIBERS

Formulas are presented for designing an optical system which couples the light beam from a source into an optical fiber. These formulas are based on the standard formulas of geometric optics. For a laser, the design is straightforward since essentially all of the laser output can be coupled into the fiber. In addition, a lamp source is considered and a formula for the lamp wattage is derived.

Coupling of Source to Fiber

The light from a source needs to be focussed onto the input end of the optical fiber. This would be done with a converging lens; and we shall describe its behaviour using the standard law of the lens derived from geometric optics. The optical arrangement is shown in Figure 1 where the beam from the source is shown as starting off from the object plane with a beam diameter D and an angular divergence α. The lens is of sufficient radius to collect the beam and converge it onto the end of the fiber located in the image plane. The spot on the lens illuminated by the source beam has radius R_{source}. The fiber has a core of diameter d and an acceptance half angle θ. (The "numerical aperture" of the fiber is N.A. = sin θ, which we shall approximate as θ itself.) Light which strikes the end of the fiber at an angle greater than θ will not be accepted - it will escape through the side of the fiber, being too close to normal incidence inside the core to experience total internal reflection. The cone of acceptance thus intersects the lens in a circle of radius R_{fiber}.

In Figure 1 we have drawn the case where the source is optimally matched to the fiber and $R_{source} = R_{fiber} = R$. For a higher quality source, all of the beam will be accepted by the fiber with room to spare. For a lower quality source, some of the light will be wasted.

When focussing is done, the law of the lens will be satisfied and we will have

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{F} \qquad \text{Eq 1}$$

where u is object distance and
v is image distance.

The magnification M is defined as the image size relative to the object size leading to

$$M = \frac{d}{D} = \frac{v - F}{F} \qquad \text{Eq 2}$$

The last equality comes from similar triangles. From this we find the image distance

$$v = F(1 + M) \qquad \text{Eq 3}$$

Now the acceptance angle for the fiber is specified by the manufacturer in terms of the numerical aperture. For the case shown in Figure 1, we would have

$$\theta = \frac{R}{v}, \text{ or } R = \theta v \qquad \text{Eq 4}$$

using the approximation $\tan \theta = \theta$.

Similarly, considering the object side of the lens, we would have

$$R = \alpha u \qquad \text{Eq 5}$$

Eliminating R from Eq 4 and Eq 5, and substituting for v from Eq 3, u from Eq 1, and M from Eq 2, we find

$$D\alpha = d\theta = d \times N.A. \qquad \text{Eq 6}$$

Eq 6 is an example of the Brightness Theorem. For 100% acceptance of the light, it is necessary to have

$$D\alpha \leq d\theta \qquad \text{Eq 7}$$

If $D\alpha$ is greater than $d\theta$, then light is lost. Assuming uniform intensity in the light beam, the fraction of the input beam which would be accepted would be

$$e_{accept} = \left(\frac{R_{fiber}}{R_{source}} \right)^2 = \left(\frac{d\theta}{D\alpha} \right)^2 \qquad \text{Eq 8}$$

Laser Sources

Lasers are commonly specified by their spot size D, and angular divergence α. Thus the above section is written in terms of laser parameters. A high-quality laser will have a beam approaching the diffraction limit, in which case we would have $D\alpha \approx \lambda$, the wavelength of the light. For multi-mode fibers, the fiber will have $d\theta$ equal to several wavelengths, and all of the laser light will be accepted by the fiber. However, with a low-quality laser with multi-mode output, it is possible that light could be lost.

Conventional Sources

Incandescent lamps and gas discharge lamps emit light in all directions and therefore require an optical light collecting system, as shown in Figure 2. Here, the emitter has linear dimension ℓ, which would be the filament length or arc length. Typically, a

parabolic reflector and condensing lens would be used, with a small f-number for large collection efficiency.

To derive an approximate formula for the light collection efficiency, consider a cube surrounding the emitter, with 1/6 of the light falling on each wall. Now consider a reflector and condensing lens which together intersect the light which would fall on two of these walls. Such a condensing arrangement would have an f-number of approximately 1/2, and would have a collection efficiency of 1/3. Considering an isotropic emitter, then, the fraction of the light collected would be

$$e_{coupling} = \frac{1}{3}\left(\frac{0.5}{f}\right)^2 = \frac{1}{12}\left(\frac{D}{F_c}\right)^2 \qquad \text{Eq 9}$$

where F_c is the focal length of the condenser lens and its diameter is D. With such a reflector and condensing lens, a "parallel" beam of light would be produced by a conventional source.

The beam diameter would be that of the condensing lens D. The angular divergence of the beam would be

$$\alpha = \frac{\ell}{F_c} \qquad \text{Eq 10}$$

where ℓ is the emitter length.

The condition for optimal matching to a fiber of core diameter d and numerical aperture θ, taken from Eq 7 is

$$D\frac{\ell}{F_c} \leq d\theta \qquad \text{Eq 11}$$

Thus, the largest condensing lens (smallest f-number) which can be used has a speed of

$$S_{opt} = \frac{1}{f} = \frac{D}{F_c} = \frac{d}{\ell}\ \text{N.A.}$$

Such an optimum condensing system yields a source beam which can be 100% accepted by the fiber. In this case, the collection efficiency is

$$e_{coupling} = \frac{1}{12}\left(\frac{d}{\ell}\ \text{N.A.}\right)^2 \qquad \text{Eq 12}$$

If the emitter has an efficiency e_{elect} for converting electrical power into light of useful wavelengths, then the lamp power required is

$$P_{elect} = \left[e_{elect}\ \frac{1}{12}\left(\frac{d}{\ell}\ \text{N.A.}\right)^2\right]^{-1} P_{fiber}, \qquad \text{Eq 13}$$

where P_{fiber} is the optical power accepted by the fiber,

d is the fiber diameter,

N.A. is the fiber's numerical aperture,

ℓ is the arc length (or arc diameter, if larger).

A factor of safety should be added to the above power estimate to allow for losses which have not been included in the calculation.

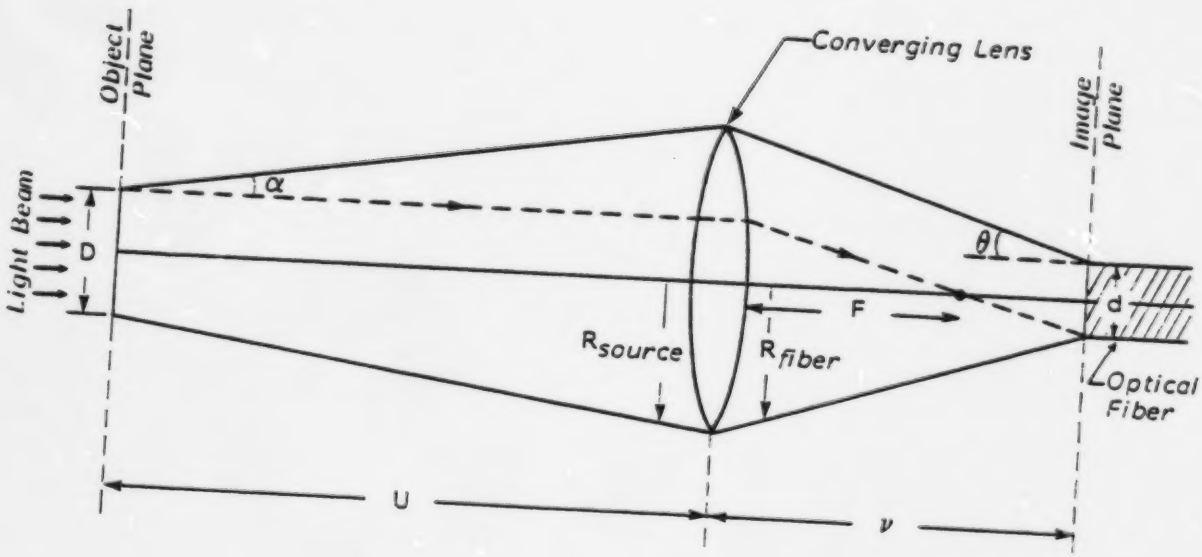

FIGURE 1

COUPLING A LIGHT BEAM INTO AN OPTICAL FIBER

A light beam of diameter D and angle of divergence α crosses the object plane at distance U from a converging lens of focal length F. The input end of an optical fiber is positioned in the image plane at distance ν-F beyond the focal point. The fiber has acceptance half-angle θ obtained from the manufacturer's quoted numerical aperture (N.A. = sin θ). The case shown is for optimal matching of source size and divergence to fiber diameter and numerical aperture. For a laser as source, the beam diameter is the laser output spot size. If an arc lamp or other conventional source is used, it is the diameter of the condensing lens.

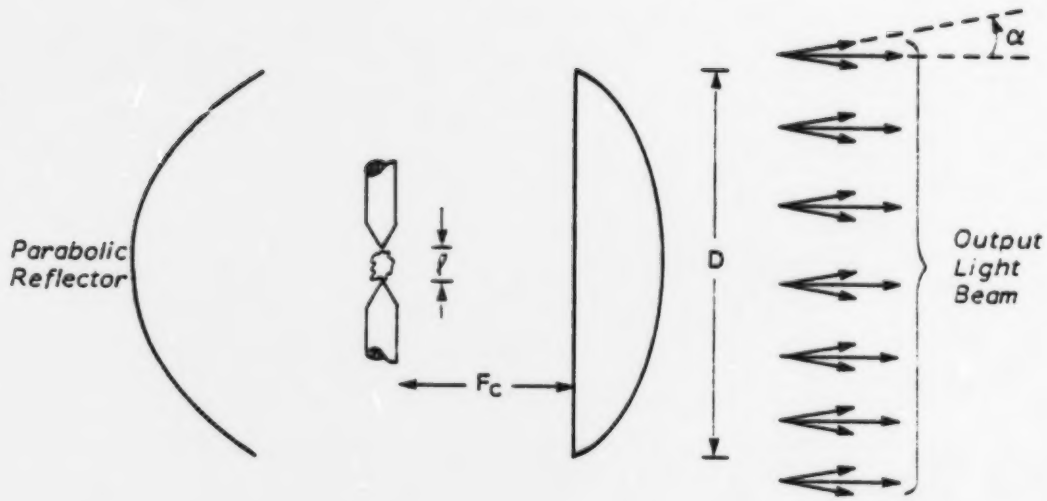

FIGURE 2

CONDENSING OPTICS FOR CONVENTIONAL SOURCE

A conventional emmiter such as an incandescent filament, flashtube, or arc lamp of dimension ℓ is placed at the focal point of a parabolic reflector on one side and a condensing lens of diameter D and focal length F_c on the other side. Such a conventional (non-laser) source then has an output light beam of diameter D and angular divergence $\alpha = \ell / F_c$.

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